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Understanding Undergraduate Research Experiences through the Lens of Problem-based Learning: Implications for Curriculum Translation

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Understanding Undergraduate Research Experiences through the Lens of Problem-based Learning: Implications for Curriculum Translation

Olga Pierrakos, Anna Zilberberg, and Robin Anderson

Abstract

There has been much criticism about science, technology, engineering, and mathematics (STEM) education not focusing enough on problem solving, especially in authentic real-world contexts which are most often associated to ill-structured domains. To improve education, it is essential that curricula promote high levels of cognitive development by exposing students to authentic problems. Problem-based learning (PBL) is a student-centered pedagogy that offers a strong framework upon which to build a curriculum to teach students essential problem solving skills. An authentic problem-solving experience, which is highly valued and promoted outside of the classroom yet almost nonexistent in the classroom, is undergraduate research (UR). Herein, the goal was to understand the nature of UR problems as a means of developing recommendations for translating UR problems and experiences into the classroom using PBL methodologies. Using survey design, data were collected from sixty students participating in summer undergraduate research experiences. Our findings revealed that moderately structured and fairly complex UR problems are well-suited for PBL implementation in the classroom because they trigger the use of multiple cognitive operations in the context of a continuously changing, dynamic, and interdisciplinary team environment.

Keywords: problem based learning, undergraduate research, complex problem solving

Introduction

Problem solving has been defined as “any goal-directed sequence of cognitive operations” (Anderson, 1980, p. 257) and according to Jonassen (2000), “problem solving is generally regarded as the most important cognitive activity in everyday and professional contexts. . . . However, learning to solve problems is too seldom required in formal educational settings, in part, because our understanding of its processes is limited”(p.

63). To add to this, a number of national reports consider current education inadequate to prepare future scientists and engineers to solve the complex problems of the future (COMPETES Act; National Academy of Engineering, 2005; Committee on Science Engineering and Public Policy, 2006; Friedman, 2005; Boyer Commission Report, 1998 and 2002; National Science Foundation, 1996; American Association for the Advancement of Science, 2002; National Research Council, 2003). These issues are increasingly important because as real-world practice is more suffused with complex and ill-structured problems and the pace of technological change becomes more rapid, future scientists and engineers are expected to offer technical ingenuity and adapt to a continuously evolving environment. It is thus imperative for STEM students to begin the real-world practice of problem solving within the undergraduate curriculum.

Problem-based learning (PBL), having historical foundations in medical education (Barrows, 1985; Barrows and Tamblyn, 1980), is a powerful student-centered pedagogy that offers a strong framework upon which to build a curriculum that will allow all students, particularly science, technology, engineering, and mathematics (STEM) students, to learn these essential, real-world, problem solving skills. In fact, a large body of literature highlights the successes of PBL in many domains and in support of many different student learning outcomes (e.g., problem solving, critical thinking, motivation, knowledge retention), and showcases PBL as a pedagogical vision rooted in practical experiences (Graff and Kolmos, 2007; Du, Graaff, & Kolmos, 2009; Woods, 1994; Schmidt, 1983; Barrows and Tamblyn, 1980).

Although PBL problems can take on a variety of forms (Du et al., 2009; Kolmos, Graaff, & Du, 2009; Ravitz, 2009; Jonassen and Hung, 2008; Savery, 2006), prior research indicates that PBL problems should be open-ended with a moderate degree of structuredness, authentic by being contextualized in real-world workplace settings, complex enough to be challenging and engaging to students' interests, adapted to students' cognitive development and prior knowledge, and amenable to problem examination from multiple perspectives (Jonassen and Hung, 2008). Although many educators see PBL as a classroom-based strategy, in actuality we can learn a lot from authentic and real-world problem-solving experiences that can be translated into classroom-based PBL experiences. In engineering education, the most common of these experiences is design, which is integral in engineering practice and has also become integral to most engineering programs (most often as capstone experiences).

One kind of authentic and real-world problem solving experience that is highly valued and promoted outside of the classroom (Russell et al., 2007; Hunter, Laurson, & Seymour, 2007), yet is almost nonexistent in the classroom, is academic research or undergraduate research (UR). Unlike most traditional course-based problems that have a concrete and clear finale, UR experiences are unique because they highlight problem solving through the lens of discovery (whether that discovery is new knowledge, a new technology, or a

new process or method) and lifelong learning. These experiences are also highly promoted, especially by the National Science Foundation (NSF) through its Research Experiences for Undergraduates (REU) program, because they are “one of the most effective avenues for attracting talented undergraduates to, and retaining them in careers in, science and engineering” (NSF, 2009). However, only a small percentage of engineering students get exposed to UR experiences, and this subset of students includes primarily top or high-achieving students (Pierrakos, Borrego, & Lo, 2008).

By viewing undergraduate research as a form of engineering practice that can be translated into the curriculum as PBL practice, the goal of the research presented here is to understand the nature of undergraduate research problems and what students learn during these experiences as a means of also understanding how we can transfer these authentic problem solving skills into the classroom, so more students can get exposed to research as a problem solving process. Using PBL theory on problem classification, grounded on measures of problem complexity and structuredness (Jonassen and Hung, 2008), we developed and utilized a survey that incorporated open-ended and Likert scale items to collect data from sixty students participating in summer undergraduate research experiences. The overarching research question was:

Through the lens of PBL theory, what is the nature of undergraduate research problems in regards to complexity and structuredness?

In addressing this question, we hope to not only contribute to our understanding of UR problems and students’ learning, but also gain insight into how PBL pedagogies can support research problem solving. By understanding UR problems through PBL theory, we will gain insight into the extent to which UR problems fit a PBL pedagogy, with the goal of ultimately translating such authentic, real-world problem solving from research contexts into undergraduate courses and curricula.

Literature Review

PBL encompasses not only a wide range of practices, but also a wide range of implementation models (Du et al., 2009; Kolmos et al., 2009; Ravitz, 2009; Savery, 2006). For example, de Graaff and Kolmos (2003; 2007) showed that there are three kinds of learning that seem to cut across many PBL models, namely cognitive learning (having a focus on the problem and the process of problem solving), content learning (having a focus on interdisciplinary learning), and collaborative learning (having a focus on team-based learning). Further, Savin-Baden proposed categorizing different PBL implementations using six different dimensions: knowledge, learning, problem, students, facilitators, and assessment (Savin-Baden, 2000; Savin-Baden 2007; Kolmos et al., 2009).

Definitions of what constitutes PBL problems also vary widely (Du et al., 2009; Kolmos et al., 2009). For many educators, PBL refers mainly to open-ended problems that

incorporate team-based collaborative learning (Barrows, 1985; Hmelo-Silver, 2004). For researchers, there is an interest in better understanding the nature of PBL problems and experiences because not all problems are created equal. Problems have been described in terms of a) ill-defined to well-defined and routine to non-routine (Mayer and Wittrock, 1996), b) well-structured to ill-structured (Jonassen, 1997), c) external factors such as complexity, structuredness, and abstractness, and d) internal factors which are inherent to the problem solver (Smith, 1991). Understanding how aforementioned problem characteristics vary across different experiences is essential for demystifying the process of learning through PBL as well as through traditional pedagogical methods. Therefore, we will apply theoretical descriptors of the problems commonly encountered by students.

In undergraduate education, the most commonly encountered problems are well-structured with known, correct solutions often acquired from preferred solution methods (Jonassen, Strobel, & Lee, 2006; Jonassen, 1997). For students, this linear process of problem solving teaches them a procedure to be memorized, practiced, and habituated, a process that emphasizes getting answers over making meaning (Jonassen et al., 2006; Wilson, 2005; Heywood, 2005, p. 243). Although it has been assumed that well-structured problem solving skills transfer to solving complex, unstructured problems, PBL research has shown that this is not the case (Cho and Jonassen, 2002; Dunkle, Schraw, & Bendixen, 1995; Hong, Jonassen, & McGee, 2003; Simon, 1978). When students attempt to apply to ill-structured domains the strategies they have used effectively for understanding well-structured domains (e.g., in introductory learning), they make errors of oversimplification, overgeneralization, and "overreliance" on context-independent representations (Spiro et al., 1988). It is thus critical for students to gain exposure to ill-structured problem solving during their undergraduate education. Such ill-structured, authentic problems are likely to be found outside of the classroom walls, such as in the research laboratory or an industry setting.

Research Experiences for Undergraduates (REU) funded by the National Science Foundation (NSF) is a widely supported program through which undergraduate students have an opportunity to actively participate in an authentic research study. The REU program, with more than 600 sites around the world, presently funds over 1000 active awards that total over \$327 million (NSF, 2009). In spite of such widespread support and belief in the value of undergraduate research, few well-grounded research and evaluation studies exist (Celia, 2005). Most of the existing literature reveals the predominance of program descriptions, explanation of models, and evaluation efforts, rather than studies grounded in empirical research. In fact, research and evaluation studies examining the benefits of undergraduate research have started to appear in publication only recently, with some of the identified benefits including: 1) retention for underrepresented groups, 2) increased interest in the discipline, 3) critical thinking skill gains, 4) increased self-confidence, and 5) clarification of career goals (Russell, Hancock, & McCullough, 2007; Hunter et al., 2007;

Seymour, Hunter, Laursen, & DeAntoni, 2004; Celia, 2005; Lopatto, 2004; Bauer and Bennett, 2003; Zydney, Bennett, & Shahid, 2002a; Zydney, Bennett, & Shahid, 2002b).

Two of the most prominent studies on undergraduate research have been the work of Elaine Seymour and her colleagues (Seymour, et al., 2004; Hunter et al., 2007), who conducted a five-year study at four liberal arts colleges with a long history of undergraduate research programs; and the work of Russell et al. (2007; 2005), who conducted a nationwide, large-scale evaluation of undergraduate research (N=3,400) via SRI International under contract to NSF. Synthesizing the work of these researchers led us to conclude that undergraduate research experiences: 1) were important in shaping career decisions and interests, 2) encouraged students' intellectual, personal, and professional development, and 3) aided students to think like scientists. Although both of these studies were extensive and provided in-depth inquiry about the benefits of undergraduate research, specific problem solving skill gains and cognitive abilities were not assessed, nor was the nature of problem solving during these experiences. This paper aims to provide further insights regarding the nature of UR problems and experiences as a means of translating such unique and beneficial experiences into the classroom via PBL methodologies.

Methodology

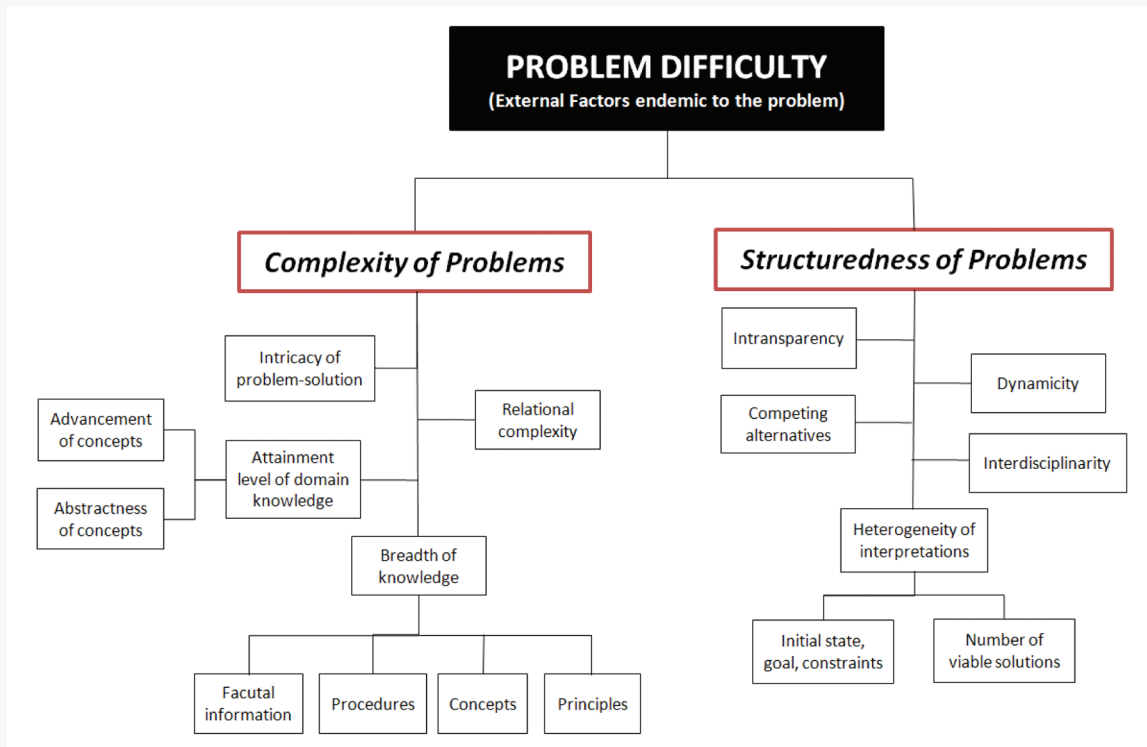
In this section, we outline the theoretical framework and methods used to answer the research question. After presenting the theoretical framework, the item development process and data collection strategies are described. Next, the data analytic methods are presented. Finally, participants' demographic information is presented.

Theoretical Framework

Jonassen and Hung's (2008) theoretical conceptualization of problem difficulty was used here as a theoretical framework, which allowed for a systematic and integrated analysis of UR problems. Figure 1 below provides a visual depiction of Jonassen and Hung's theoretical framework of the hierarchical structure of problem difficulty. Broadly speaking, the comprising elements of this structure are positioned under two subcategories: 1) problem structuredness and 2) problem complexity. In the section that follows, we briefly explicate each of these elements.

Problem complexity encompasses the following features:

1. **Intricacy of Problem-Solution.** This parameter refers to the number of obstacles one has to overcome to solve a particular problem. Sometimes referred to as solution path length (Hays & Simon, 1974), the intricacy of the solution can be gauged through the time required to solve a problem.
2. **Relational Complexity.** Relational complexity, similar to the cognitive load, refers to the number of possible alternatives a problem-solver needs to consider.

Figure 1. Problem difficulty classification framework based on Jonassen & Hung (2008)

Solving more advanced or real-life problems requires a degree of relationally complex thinking, as opposed to a linear, straight-forward reasoning (Jonassen & Hung, 2008).

3. **Attainment Level of Domain Knowledge.** This parameter pertains to the difficulty of the domain knowledge that one needs to master in order to apply this knowledge during problem solving. Abstract concepts are generally harder to grasp than concrete concepts (Jonassen & Hung, 2008).
4. **Breadth of Knowledge.** This category pertains to the problem space or scope and refers to “factual information, concepts, principles, and procedures” (Sugrue, 1995, qtd. in Jonassen & Hung, 2008). The more conceptual and applied knowledge one needs to complete a problem, the more complex the problem.

Problem structuredness encompasses the following features:

1. **Intransparency.** Degree of intransparency refers to the number of unknowns in the problem. The more unknowns there are, the higher the degree of intransparency and thus the more ill-structured the problem.
2. **Dynamicity.** Dynamicity concerns the “emergent properties” (p. 14) appearing in the problem. As such, dynamic problem-solvers have to constantly adjust and re-evaluate their assumptions (Jonassen & Hung, 2008). Higher degrees of dynamicity indicate more ill-structured problems.

3. Competing Alternatives. This parameter refers to the number of viable alternative solution paths. Ascertaining the legitimacy of these competing alternatives contributes to the degree of problem structuredness (Jonassen & Hung, 2008).
4. Interdisciplinarity. This aspect refers to the scope of interdisciplinary knowledge one needs to apply in order to solve a problem. More ill-structured and complex problems require integration and synthesis of multiple disciplines (Jonassen & Hung, 2008).
5. Heterogeneity of Interpretations. This parameter deals with the extent to which the problem is open to interpretation. That is, if a problem is really well-defined, with clearly delineated initial state, goal state, and constraints, it can be considered homogenous in interpretations and will rank lower on problem structuredness. However, if a problem solver first has to define different aspects of the problem before contouring the solution, it makes the problem more ill-structured (Jonassen & Hung, 2008).

The next section outlines the procedure employed to operationalized the theoretical framework and design a survey instrument to tap into the problem difficulty elements outlined by Jonassen & Hung (2008).

Item Development and Data Collection

The theoretical framework outlined above guided the development of the survey items pertinent to undergraduate research contexts. The items were developed by members of an interdisciplinary research team, involving experts in engineering mechanics, engineering education, psychology, and measurement. The resulting instrument went through several iterations before the final version was agreed upon. The items on the survey were designed to address problem difficulty parameters described in the previous section. Table 1 presents the survey items along with the corresponding problem difficulty parameter. The survey included a mix of both Likert scale and open-ended items, which allowed for triangulating qualitative and quantitative data and thus offsetting the limitations inherent in both. Namely, concurrent nested strategy commonly used in mixed-methods research was employed in this study (Creswell, 2003, p. 218). This strategy allowed for interpreting both types of data simultaneously in a single research study.

The survey was administered online at two time points: before students started their UR, and upon completion of their UR. Due to the confidentiality concerns, participant identifier information could not be collected. Therefore, aggregate data were compared to gauge the differences in student development over the course of UR. This design feature is further explicated in the Limitations section towards the end of the paper.

Table 1. Mapping of problem difficulty survey items (column 1) with complexity and structuredness parameters (column 3) based on Jonassen and Hung (2008). The designation of whether survey items are qualitative and quantitative is also included in column 2.

Survey Item(s) quaL = qualitative & quaN= quantitative		Problem Difficulty Parameter(s)
What domain knowledge (defined as facts, concepts, principles, skills, procedures, etc.) was needed to work on this research project? It may help to think about this domain knowledge in terms of course subject topics.	quaL	Breadth of Knowledge (Complexity)
On a scale of 1 to 10, how much of this domain knowledge did you possess when you started your undergraduate research project?	quaN	Attainment of Domain Knowledge (Complexity)
On a scale of 1 to 10, how much of this domain knowledge did you possess at the end of your undergraduate research project?	quaN	
On a scale of 1 to 10, how would you rate the difficulty of the domain knowledge that was needed to work on this undergraduate research project?	quaN	
How much time did you spend on each of the following project stages*? Approximate times should be entered as percentages and the total should equal 100%.	quaN	Intricacy and Relational Complexity (Complexity)
On a scale of 1 to 10, how would you rate the difficulty of conducting each of the following project stages*?	quaN	
Overall, on a scale of 1 to 10, how challenging was this undergraduate research experience?	quaN	
On a scale of 1 to 10, how well-defined were each of the following project stages*? In answering this question, it may help to think about how much well-defined direction you received from your research supervisor(s)/mentor(s).	quaN	Intransparency, Heterogeneity, Dynamicity, and Competing Alternatives (Structuredness)
How many possible alternative solutions/paths did you consider in regards to methods, procedures, analysis, etc. during your project?	quaL	
What were the biggest challenges you faced during this undergraduate research experience?	quaL	
In thinking about the domain knowledge listed above, what disciplines do you think were needed to work on this research project? It may help to think about this disciplinary domain knowledge in terms of college majors or departments.	quaL	Interdisciplinarity (Structuredness)

* The project stages refer to 1) Defining the problem, 2) Establishing objectives and constraints, 3) Selecting methods and procedures, 4) Collecting data, 5) Analyzing data, 6) Project management, 7) Documenting results.

Data Analysis Methods

Data analysis of the qualitative survey items began with the iterative development of a coding framework (Attride-Stirling, 2001). Thematic network analysis, recommended by Attride-Stirling for interpreting complex qualitative data, was deemed most appropriate because it allowed for the systematic extraction of common themes and evaluation of the relative importance of each. Two researchers developed a coding framework by noting common thematic threads surfacing in the responses. The final coding framework was evaluated by a third independent researcher and was used to code the data into thematic groups. Subsequently, these groups were merged into common themes.

Data collected with the quantitative items were aggregated and descriptive statistics were tabulated and graphed to facilitate interpretation.

Participants

The sample consisted of 60 participants recruited from two separate NSF funded REU sites. Site one had approximately 10 participants and had a focus on computer integrated surgi-

cal systems and technology, whereas site two had a nanotechnology focus and approximately 50 participants conduct their undergraduate research across twelve institutions nationwide. Participants came from 49 universities and twelve different majors including science majors ($N=20$ from biology, biochemistry, chemistry, math, and physics majors) as well as engineering disciplines ($N=40$ from biomedical, chemical, computer, electrical, engineering physics, materials science, and mechanical engineering majors). The sample was composed of 11 rising sophomores (18.3%), 20 rising juniors (33.3%), and 29 rising seniors (48.3%) ("rising" refers to a student who had completed all the courses to qualify for the next academic year). As such, upperclassmen comprised 82% of the sample. Such an academic composition in which the majority of student participants are rising juniors and seniors is fairly typical of REU sites (Pierrakos and Trenor, 2009; Trenor and Pierrakos, 2008; Pierrakos et al, 2008). Also typical of REU sites is the recruitment of students with strong academic backgrounds such as high grade point averages (GPA). In the sample herein, 48 students (80%) listed a GPA equivalent to an A or A- and the remaining 12 (20%) reported a GPA in the B or C range. The sample was fairly balanced in gender: 28 females (46.6%), 24 males (40 %), and 8 students (13%) who did not report gender. The majority of participants (36, 60%) identified themselves as Caucasian, followed by 9 Asian or Asian American (15%), 5 African American (8.3%), and 10 (6%) representing other ethnicities or declining to report their ethnicity.

To better understand the REU participants' academic background, we asked students to identify prior project experience in the form of undergraduate research, industry internships/co-ops, technical service learning projects, and design projects. Survey responses revealed that 45 of the REU students (75%) had participated in at least one prior undergraduate research experience. More specifically, 30 (50%) of the students had participated in one other UR experience, 9 (15%) had participated in two other UR experiences, and 6 (10%) had participated in three other UR experiences. In regards to industry internships or co-ops, technical service-learning projects, and design projects, respectively 9 (15%), 16 (26%), and 28 (46%) of the students had participated in such experiences in the past. The majority of students that had previously participated in design projects were engineering majors.

Results

In this section, our focus is on understanding the nature of undergraduate research (UR) problems. More specifically, we want to better understand these problems through the lens of problem structuredness and problem complexity. Thus, the following two subsections include results that map to the survey items in table 1.

Complexity of Undergraduate Research (UR) Problems

We begin examining UR problem complexity by addressing the breadth of knowledge required to work on and solve such problems. From table 1, breadth of domain knowledge is assessed by an open-ended question in which undergraduate researchers were asked to identify and list the disciplinary domain knowledge that was needed to work on their research projects. Domain knowledge was defined as disciplinary concepts, principles, facts, skills, procedures, and so on. To help guide the undergraduate researchers with this definition, a suggestion was provided in the survey for students to think about disciplinary domains in terms of course subject topics. With over fifty unique domain knowledge responses encompassing topical subjects across STEM fields, the responses were organized and coded into nine major disciplinary domain organizing themes: mathematics, biology, biochemistry, chemistry, physics, engineering, materials science, computer and computational tools, and experimental tools. These nine organizing themes are listed in column one of table 2. Although it is beyond the scope of this paper to list all the subthemes, it is important to illustrate some examples. For the mathematics organizing theme, the corresponding subthemes were algebra, calculus, differential equations, and statistics. For the biology organizing theme, corresponding subthemes included anatomy, physiology, and molecular biology. For the engineering organizing theme, corresponding subthemes included fluid mechanics, thermodynamics, heat transfer, design skills, statics, dynamics, kinetics, and signal processing.

Table 2 summarizes all participant responses of disciplinary domain knowledge needed for the UR project, including descriptive statistics, range of subthemes identified, mean value of subthemes identified, and number and percentage of individuals who

Table 2. Descriptive statistics of participants' responses on disciplinary domains needed to work on their research. The descriptive statistics include the range of subthemes identified, the mean value of subthemes identified, as well as the number and percentage of individuals who identified the theme.

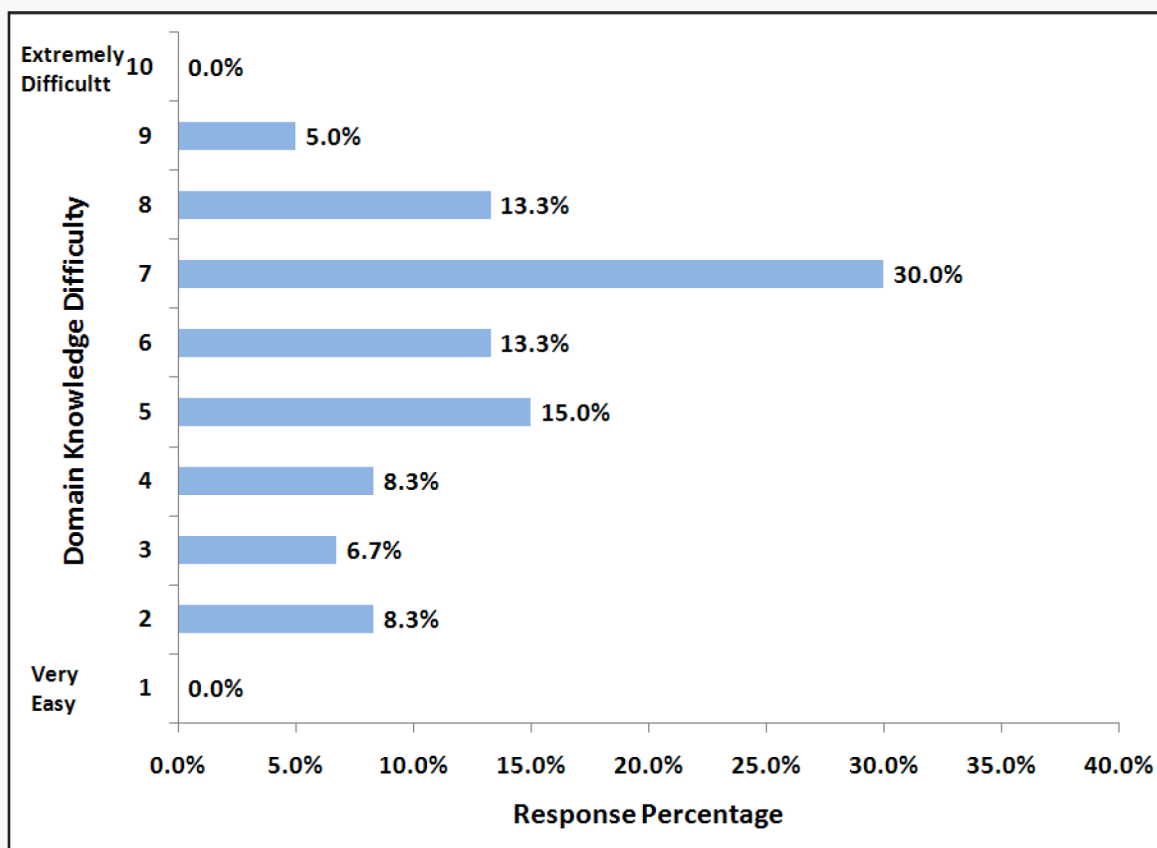
STEM Disciplinary Domains (Organizing Themes)	N = 60		
	Range	Mean	N (%)
Mathematics	0 to 3	1.23	58 (97%)
Physics	0 to 4	1.07	41 (68%)
Engineering	0 to 4	0.73	34 (57%)
Computational Tools	0 to 2	0.60	30 (50%)
Chemistry	0 to 2	0.52	28 (47%)
Experimental Tools	0 to 3	0.40	18 (30%)
Biology	0 to 2	0.28	15 (25%)
Materials Science	0 to 3	0.28	14 (23%)
Biochemistry	0 to 1	0.07	4(7%)
Range	2 to 13		
Mean (St. Dev.)	5.2 (1.9)		

identified the theme. The domains are listed in the order of frequency of occurrences. On average, students listed about five domain knowledge topics. The fewest domain knowledge topics a student listed was two and the most was thirteen. Overall, the most frequently listed disciplinary domain topics pertained to mathematics and physics. The least frequently reported topics pertained to natural sciences and experimental tools.

Next, we examined students' self-reported attainment of domain knowledge, as well as the difficulty of the domain knowledge. For the domain knowledge possessed at the start of the undergraduate experience, the average rating was 4.60 (sd = 2.12) on a scale from 1 to 10 (1 – none and 10 – all). The percentage of students rating the domain knowledge possessed at the beginning of the UR as 5 and below was 70%. The mean rating for the reported domain knowledge possessed at the end of the experience was 7.97 (sd = 1.43), corresponding to a 73% increase. As per domain knowledge difficulty, the mean rating was 5.87 (sd = 1.94), with 77% of students giving a rating of 5 or above. Figure 2 presents response percentages pertaining to domain knowledge difficulty in a visual form.

The next set of survey items were designed to give us insights into the intricacy and relational complexity of UR problems. More specifically, we wanted to decompose the

Figure 2. Response percentages for survey items pertinent to domain knowledge difficulty. $N = 60$.



typical research process to gain insight into the intricacy of the solution path length and the relational complexity of the process. Based on the primary author's previous work on understanding and assessing learning during UR experiences (Pierrakos and Trenor, 2009; Pierrakos et al., 2008), we derived the following seven major stages typical of many problem solving processes, including research:

- 1) Defining and formulating the problem
- 2) Establishing objectives, requirements, and constraints
- 3) Selecting methods and setting up procedures for data collection
- 4) Collecting data
- 5) Analyzing data and making conclusions
- 6) Project management (planning, timelines, organization, etc.)
- 7) Documenting research in technical reports and presentations.

Utilizing these seven stages, three Likert scale items were included in the survey and were focused on measuring the perceived percentage of time that students spent on each of the project stages, the degree to which these stages were defined for the students, as well as the inherent difficulty of conducting each project stage.

The results from these items are summarized in table 3. Starting with estimates of percent time spent on the project stages, we observed a wide variance (looking at the ranges and standard deviations for each stage) in how students spent their time during this UR experience. Looking at the mean values, it is evident that the students spent the majority of their time (about 65%) on three stages: collecting data (~28% of their time), selecting methods and setting up procedures for data collection (~22% of their time), and analyzing data (~14% of their time). Although not shown in table 3, the stage that students rated with the highest percentage of time spent was data collection for 42% of the students, followed by selecting methods and setting up procedures to collect data for 28% of the students. The project stage that students seemed to spend the least amount of time on was project management. This may be due to mentors facilitating and guiding the management of the project and students not being integrally involved with the planning of the UR project.

Table 3. Descriptive statistics for survey item focused on assessing how undergraduate researchers spent their time (in percent format) across seven project stages.

Project Stage	Percent Time Spent on Project Stage	
	Range N=57	Mean (St. Dev.) N=57
Defining and formulating the research problem	0 - 50	10.4 (9.9)
Establishing objectives, requirements, and constraints	0 - 45	9.4 (7.5)
Selecting methods and setting up procedures for data collection	1 - 60	21.9 (17.1)
Collecting data	0 - 70	27.6 (18.7)
Analyzing data and making conclusions	0 - 45	13.9 (8.9)
Project management (planning, timelines, organization, etc.)	0 - 30	6.7 (5.6)
Documenting research in technical reports and presentations	0 - 40	10.2 (6.7)

In regards to students' ratings of difficulty of conducting the seven project stages, based on a scale of 1 to 10 (1 – very easy to 10 – extremely difficult), we observed from figure 3 that students' overall mean ratings varied from 4.26 to 6.25 (sd range from 1.9 to 2.2). Although estimating statistical significance differences is not informative in this case, given the small sample size, it is of interest to scan the differences among various project stages. The three project stages with the highest difficulty ratings, all above 5, were collecting data, selecting methods and setting up procedures for data collection, and analyzing data and making conclusions. Further, we estimated the percentage of students who rated the difficulty of the project stages at 6 and above (i.e., difficult range) in comparison to students who gave a rating of 5 and below (i.e., not difficult range). From this estimation, we observed that only for analyzing data and making conclusions did the majority of students (70%) rate the project stage to be in the difficult range (6 or above).

The last survey item that provided insight into the complexity of UR problems asked undergraduate researchers to rate on a scale of 1 to 10 (1 – not at all challenging to 10 – very challenging) how challenging the UR experience was overall. Student responses to this survey item are summarized in figure 4. Overall, the data revealed that the mean

Figure 3. Bar chart of students' mean ratings of difficulty of conducting the seven project stages.

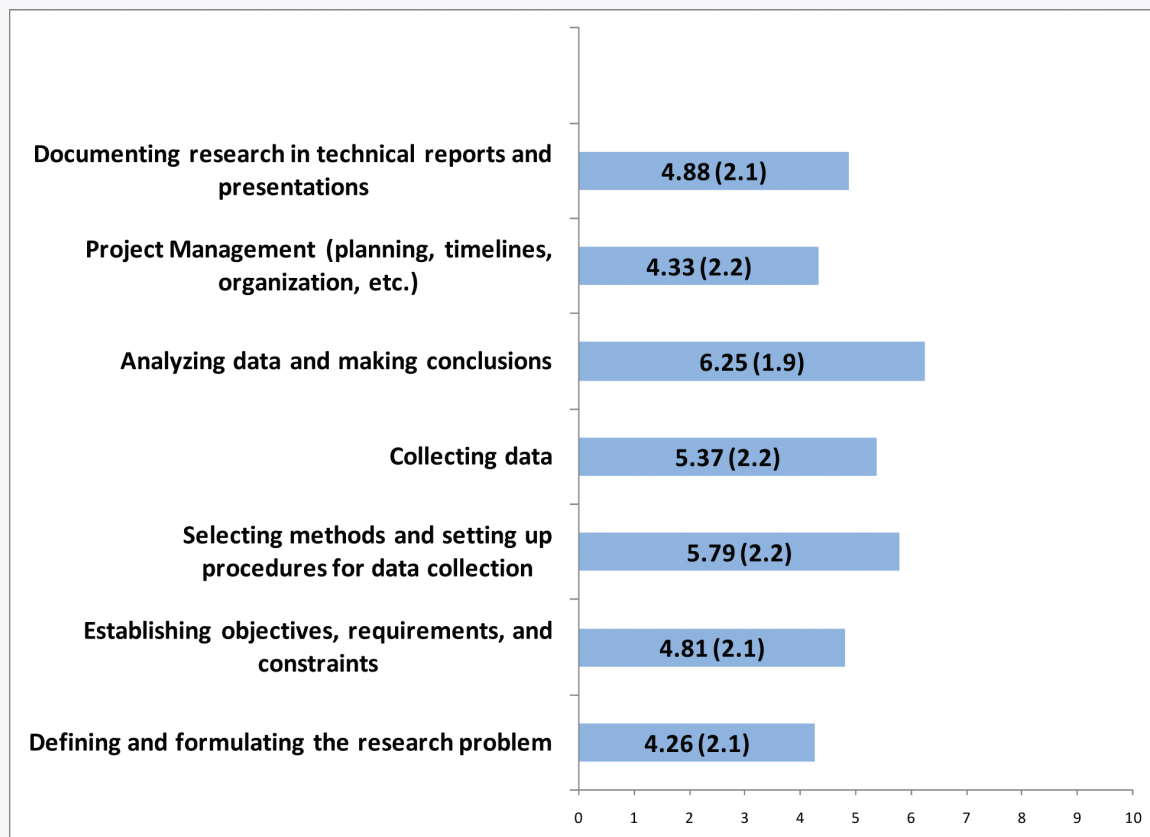
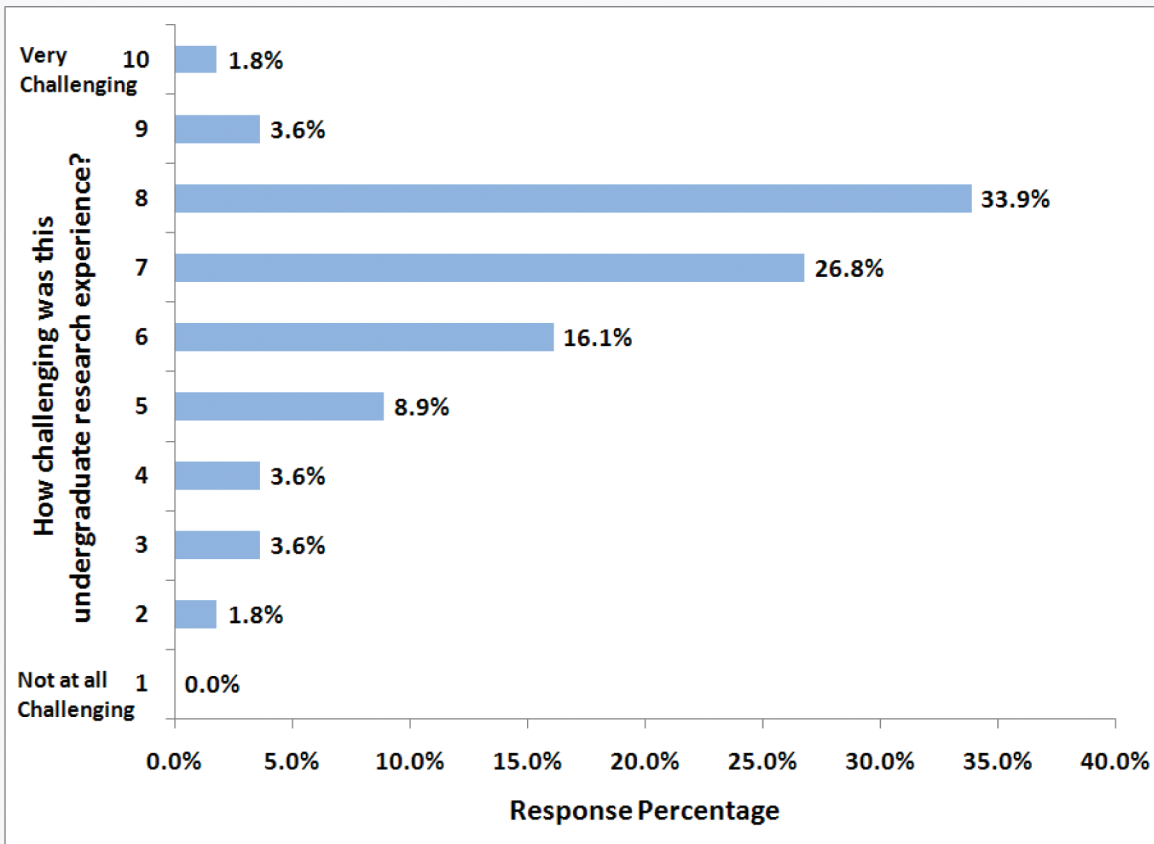


Figure 4. Response percentages for survey item pertinent to challenge of the undergraduate research experience. $N = 57$ (3 responses were incomplete).



rating for all students was 6.81 ($sd = 1.62$), with about 82% of the students giving a rating or above (i.e., challenging range); these results suggested that UR was perceived as a rather challenging experience for students.

Structuredness of Undergraduate Research (UR) Experiences

Problem structuredness, as described by Jonassen and Hung (2008), encompasses five categories: intransparency, competing alternatives, dynamicity, heterogeneity of interpretations, and interdisciplinarity. Because these categories are coupled in many ways, particularly the first four listed, it was very difficult to operationalize these into survey items that capture each parameter individually. However, we were able to develop six survey items, three Likert scale and three open-ended, to provide insights about the structuredness of UR experiences. From a global perspective, structuredness can be described in terms of problems being well-structured to ill-structured (Jonassen, 2002) and we will discuss the results in this section from that perspective.

To better understand the structuredness of the stages, students were also asked to rate how well-defined each of these project stages was on a scale of 1 to 10 (1 – not

well-defined at all and 10 – extremely well-defined). Descriptive statistics (mean values, standard deviation, and frequency statistics) are summarized in table 4 and figure 6. As depicted in figure 6, students' mean ratings varied from 6.96 to 8.05 (sd range from 1.8 to 2.4). From the data shown in table 4, we can estimate the percentage of students who gave a rating of 6 and above (i.e., well-defined range) in comparison to students who gave a rating of 5 and below (i.e., ill-defined range). From this estimation, we observe that the majority of students (75% to 91%) rated the project stages to be in this well-defined range (6 or above). These results suggest that not only were all seven project stages rated fairly consistently (i.e., one project stage did not appear to be more well-defined than another), but that overall these stages were fairly well-defined for the students. However, it might also indicate that the survey is not sensitive enough to detect the differences. For this reason, the conclusions made based on this information should be considered preliminary and additional validity evidence for the scale should be garnered.

To gain further insights into the structuredness of UR problems, we asked students two open-ended questions designed to capture the dynamicity and intransparency of the solution path, as well as to understand the challenges students faced during the UR experience. Both of these questions were coded using the qualitative scheme described in the Methodology section. Starting with survey item "How many different alternative solutions did you consider?," table 5 presents the coding framework (themes, definitions,

Table 4. Descriptive statistics on students' ratings of how well-defined each of the seven project stages was during the UR experience. The ratings are based on a scale of 1 to 10 (1 – not well-defined to 10 – extremely well-defined).

List of Seven Project Stages	N (%), N=56									
	1 – not well defined	2	3	4	5	6	7	8	9	10 – extremely well defined
Defining and formulating the research problem	1 (1.8%)	1 (1.8%)	3 (5.3%)	3 (5.3%)	4 (7%)	3 (5.3%)	12 (21.1%)	6 (10.5%)	9 (15.8%)	15 (26.3%)
Establishing objectives, requirements, and constraints	1 (1.8%)	1 (1.8%)	4 (7%)	2 (3.5%)	5 (8.8%)	6 (10.5%)	9 (15.8%)	8 (14%)	13 (22.8%)	8 (14%)
Selecting methods and setting up procedures for data collection	0 (0%)	1 (1.8%)	1 (1.8%)	2 (3.5%)	5 (8.8%)	5 (8.8%)	8 (14%)	6 (10.5%)	14 (24.6%)	15 (26.3%)
Collecting data	0 (0%)	1 (1.8%)	2 (3.5%)	3 (5.3%)	3 (5.3%)	5 (8.8%)	7 (12.3%)	13 (22.8%)	11 (19.3%)	12 (21.1%)
Analyzing data and making conclusions	0 (0%)	2 (3.5%)	6 (10.5%)	1 (1.8%)	6 (10.5%)	5 (8.8%)	8 (14%)	13 (22.8%)	8 (14%)	8 (14%)
Project management (planning, organization, etc.)	1 (1.8%)	2 (3.5%)	5 (8.8%)	2 (3.5%)	4 (7%)	6 (10.5%)	10 (17.5%)	10 (17.5%)	7 (12.3%)	10 (17.5%)
Documenting research in technical reports and presentations	0 (0%)	0 (0%)	2 (3.5%)	3 (5.3%)	0 (0%)	3 (5.3%)	8 (14%)	14 (24.6%)	15 (26.3%)	12 (21.1%)

examples of responses, and frequency statistics) for students' responses to this question. Three broad themes emerged: 1) *very well-structured* (the solution path was very well-defined and there were no alternative solutions), 2) *somewhat structured* (the solution path was somewhat defined and there were several alternative solutions), and 3) *very ill-structured* (the solution path was very undefined and there were multiple alternative solutions). Typical responses for each of these themes are included in column three of table 5. From the frequency statistics, we observe that the theme *somewhat structured* was the most prevalent with 58% of the students describing the solution path in this way. The second most prevalent theme was *very ill-structured* with about 27% of the students describing their solution path in these terms. About 15% of the students described their solution path as being *very well-structured*. It should also be pointed out that some sub-themes emerged under major theme somewhat structured, and these tended to represent explanations or reasons for the solution path having few alternative solutions. Although not included in table 5, these subthemes dealt with time constraints, working with other people, and obstacles faced, all of which may be reasons for the undergraduate researchers deciding to take an alternative solution path.

Undergraduate researchers were also asked to identify the biggest challenges faced during their undergraduate research experience. Responses to this open-ended question gave us insights into the aspects of the experience that were most challenging or

Table 5. Summary of coding themes, theme definitions, examples of responses, and descriptive statistics for the qualitative survey item "how many different alternative solutions did you consider?"

Coding Themes	Theme Definition	Examples of Responses	f (%)
Very well-structured	The solution path was <i>very well-defined and well-structured</i> . There were no alternative solutions.	"The procedure was determined before I arrived" "My methods and procedures did not change over the course of my project"	9 (15%)
Somewhat structured	The solution path was <i>somewhat well-defined and well-structured</i> . There were a few alternative solutions.	"We considered multiple options" "About halfway through the internship I tried a new procedure that worked fantastically" "We experimented with a couple of different ways to dilute the polymer and the polyacrylic acid in such a way that would give us better results"	35 (58%)
Very ill-structured	The solution path was <i>very undefined and ill-structured</i> . There were multiple alternative solutions.	"We revised our procedures A LOT! I can't remember the exact number but we had to have tried between 10-15 different things" "We constantly adjusted various parameters in our methods to maximize yield" "Many different methods were used"	16 (27%)

Table 6. Summary of challenges faced during the undergraduate experience. The table includes the coded themes, definitions, examples of responses, and frequency statistics.

Coding Themes	Theme Definition	Examples of Responses	N=60 f (%)
Learning New Knowledge and Skills	Challenges pertinent to mastering and applying new content knowledge or skills (scientific and engineering) needed for the research project.	<p>“Figuring out how to measure resist thickness w/out exposing to outside light w/out filtered yellow lights”</p> <p>“The biggest challenge was working with the delicacy of the chips I was working with”</p> <p>“Very large learning curve in image processing”</p> <p>“Working on the concepts I have not yet studied”</p>	16 (27%)
Time Constraints and Management	Challenges pertinent to issues with time – not enough time allocated, waiting too long, time management, etc.	<p>“Time. I spent a great deal of time waiting for parts ... and waiting for epoxy to dry. If I had had more time, I could have taken the measurements.”</p> <p>“Coping with late hours”</p> <p>“Figuring out how long certain tasks would take me to complete and having my professor set this time”</p> <p>“The biggest challenges for me were balancing time”</p>	11 (18%)
Team Dynamics and Communication	Challenges pertinent to all aspects of communication within a team, including understanding foreign accents, picking up on the power dynamics within a group, etc.	<p>“Language barrier, my group was all Chinese and I am terrible with accents”</p> <p>“The challenges related to communicating with people who are uncomfortable communicating in English”</p> <p>“Overcoming the sarcastic comments and busy schedules of my higher ups”</p> <p>“Interaction with my research group on a serious, professional level”</p>	7 (12%)
Funding and Equipment Limitations	Challenges dealing with funding and equipment, including budget constraints, limited or insufficient equipment resources, equipment not working, etc.	<p>“It doesn't "look good" for them to have spent 1.6 million dollars on a machine recently, and I go use another cheaper instrument”</p> <p>“Making a workable system with little to no funding to buy the tools that I needed”</p> <p>“Managing limited resources (equipment and space)”</p> <p>“Equipment being down”</p>	7 (12%)
Independence and Taking Initiative	Challenges of independent functioning and taking initiative (i.e. knowing when to work alone, when to ask for help, handling lack of supervision, etc.	<p>“Figuring out at what point I could do something independently and without supervision”</p> <p>“Learning to work on my own and solve problems without help”</p> <p>“Being able to work independently of my graduate student mentor, yet knowing when to ask for help”</p>	5 (8.3%)
Student-Mentor Relationship & Interaction	Challenges having to do specifically with mentee/mentor relationships and interactions.	<p>“Communicating with my mentor while he was out of the country was difficult...”</p> <p>“Proceeding with research during occasional absence of mentor”</p> <p>“I was not able to successfully communicate with my mentor because he was rarely available”</p>	3 (5%)
Understanding Project Requirements	Challenges pertinent to understanding the requirements and expectations of the research project.	<p>“The biggest challenge was probably getting adjusted to the level of work and dedication that was expected”</p> <p>“The biggest challenges were defining the most important project objectives”</p> <p>“Trying to understand what my PI required of me”</p>	3 (5%)

ill-structured for students. Seven major types of challenges were identified from students' responses and these are summarized in table 6, which also includes theme definitions, examples of responses, and frequency statistics. With a 27% response rate, the most frequently mentioned theme or challenge was *learning new knowledge and skills*, which dealt with the challenge of learning, understanding, and applying new concepts, domain knowledge, and skills (procedural, experimental, computational, etc.). With an 18% response rate, the second most prevalent theme pertained to *time constraints and management*, which referred to challenges of time management in regards to issues of task completion, waiting for parts or equipment, planning, and so on. With a 12% response rate, the third most prevalent theme or challenge dealt with *team dynamics and communication*. The fourth most prevalent theme or challenge was *funding and equipment limitations*, with an overall response rate of 12%. The remainder of the themes/challenges identified by the undergraduate researchers focused on *independence and taking initiative*, *student-mentor relationship and interaction*, and *understanding project requirements*.

Table 7 summarizes students' responses to two open-ended survey items, one focused on identifying the disciplines needed for the research project (project disciplinary), the other on the disciplines of the research team (team disciplinary). Starting with research project disciplinary, students' responses were coded and categorized to form thirteen distinct STEM disciplines as illustrated in column one of table 7. These thirteen distinct disciplines are representative of the research foci of the two REU sites—nanotechnology and computer integrated surgical systems and technologies—and not necessarily representative of all undergraduate research experiences. Yet, the results still provide valuable

Table 7. Descriptive statistics pertinent to disciplines needed for the research project (project disciplinary) and the disciplines of the research team (team disciplinary).

STEM Disciplinary Category	Disciplines Needed for Project (Project Disciplinary) N = 60	Disciplines of Research Team (Team Disciplinary) N=57
Electrical/Computer Eng.	23 (38%)	27 (47%)
Physics	34 (57%)	23 (40%)
Biomedical Eng.	3 (5%)	13 (23%)
Materials Science/Eng.	19 (32%)	11 (19%)
Chemistry	25 (42%)	10 (18%)
Mechanical Eng.	11 (18%)	10 (18%)
Computer Science	10 (17%)	8 (14%)
Chemical Eng.	7 (12%)	8 (14%)
Range	1 to 5	1 to 5
Biology	12 (20%)	6 (11%)
Biochemistry	3 (5%)	3 (5%)
Other Engineering	7 (12%)	3 (5%)
Mean and St. Dev.	2.7 (1.0)	2.2 (1.1)
Environmental Eng.	1 (2%)	1 (2%)
Math	3 (5%)	0 (0%)

insight into undergraduate research experiences. Overall, table 7 shows that on average students listed two to three distinct disciplines needed for their research project. The minimum listed was one discipline and the maximum was five. These results provide insight into the multidisciplinary and interdisciplinarity of undergraduate research projects.

Discussion

What Have We Learned about the Complexity of UR problems?

In assessing the breadth of knowledge required to work on and solve UR problems, we gained insight into the scale and scope of the research problems that students worked on. On average, students listed about five domain knowledge topics, of which the most frequently listed were mathematics, physics, chemistry, computational tools, and experimental tools. The greater the amount of domain knowledge required in problem solving, the greater the size of the problem space, and thus the more complex the problem (Jonassen and Hung, 2008). From a cognitive perspective, these results suggest that students needed to possess and apply a large amount of domain knowledge during the research problem solving process. Further, most of this domain knowledge probably needed to be integrated and processed in a way that continuously advanced students' knowledge base about the research, so it would be expected that the cognitive and processing loads increased over the duration of the experience. Such observations are further corroborated by the results of domain knowledge attainment, which revealed an increase (73%) from the start to the end of the experience (based on mean ratings). There was a good amount of difficulty in applying and understanding the needed domain knowledge to solve the research problem. These findings further support that problems commonly encountered during the undergraduate research experiences are moderately complex and require students to increase their cognitive and processing loads.

Not only was there complexity in the domain knowledge required, but also in the solution path. The results suggested that there was a wide variance in how students spent their time on the various project stages. In fact, students spent the majority of their time (about 65%) *collecting data, selecting methods and setting up procedures for data collection, and analyzing data*. The steps of the process were iterative and suggest some intricacy in the solution path, especially when considering that students faced unanticipated problems during each of these project stages. With 70% of the students giving a rating of 6 and above (i.e., difficult range), it was clearly evident that the most difficult project stage was *analyzing data and making conclusions*. These findings suggest that the undergraduate researchers experienced an intricate and iterative problem-solution process as they transitioned from establishing research methods to data collection, data analysis, and

other project stages. Lastly, the fact that 82% of the students gave a rating of 6 or above (i.e., challenging range, 10-pt scale) for the overall difficulty of the UR experience suggests that UR problems are fairly complex.

What Have We Learned about the Structuredness of UR problems?

Most notably, valuable insights were gained regarding the structuredness of the UR experience by assessing the dynamicity and intransparency of the solution path. The results showed that the majority of the students identified a solution path that was *somewhat defined* and involved several alternative solutions. The solution path was *very ill-structured* (an undefined solution path with multiple alternative solutions) for 27% of the students and *very well-structured* (one very well-defined solution path) for 15% of the students. These findings suggest that the majority of students integrated multiple alternative solutions during their research and used more than one solution path. Further, it was evident that there was some degree of intransparency (aspects that were not known about the problem) during this research experience and this suggests some degree of ill-structuredness in UR problems. There were several challenges that students faced which further provide insight into the structuredness of UR experiences. Some of these challenges, in order of prevalence, were learning new knowledge and skills, management, team dynamics, communication, funding and equipment limitations, and independence. These multifaceted challenges (encompassing cognitive, operational, and interpersonal elements) illustrate some degree of ill-structuredness to UR problems.

Next, the results revealed that the majority of students perceived the seven project stages as fairly well-defined. This finding is corroborated in a previous study, which used a community of practice theoretical framework to understand the UR learning environment and showed that undergraduate researchers entering research groups as “newcomers” received supervision and guidance from mentors or “old-timers” (Pierrakos and Trenor, 2009; Trenor and Pierrakos, 2008). These findings suggest that there was moderate structuredness to the research problem solving process which was in part facilitated by the multiple layers of mentoring that is typical during undergraduate research experiences.

Last, students listed an average of two to three distinct disciplines for project disciplinaryity, suggesting that UR experiences exhibit a degree of multidisciplinaryity and interdisciplinaryity, enabling students to integrate various disciplinary perspectives. This need and requirement to integrate interdisciplinary knowledge involves some degree of difficulty in cognitively constructing and understanding the problem space, which influences the problem structuredness. Further, the interconnectedness and interdependency of the various disciplines is likely to change aspects of the problem, which can make solving the problem a challenge. These observations suggest that the interdisciplinary nature of research problems can result in a degree of ill-structuredness and also in a degree of complexity.

Conclusions

Problem-based learning (PBL), with its multi-faceted structure and nature (Du et al., 2009; Kolmos et al., 2009), serves as a powerful pedagogy to expose our students to a variety of authentic and real-world problem solving environments, thus enabling different modes of thinking, learning, and problem solving. In this paper, undergraduate research (UR) experiences were investigated through the lens of problem complexity and problem structuredness. Our motivation was to understand the nature of UR problems as a means of translating and integrating research problem solving into the classroom. PBL pedagogies can certainly serve as the framework for this transferability.

According to Jonassen and Hung (2008), PBL problems should be ill-structured with a moderate degree of structuredness, authentic by being contextualized to real-world workplace settings, complex enough to be challenging and engaging to students' interests, adapted to students' cognitive development and prior knowledge, and amenable to problem examination from multiple perspectives. Our findings indicate that UR problems do in fact meet these criteria for ideal PBL problems. More specifically, it is worth highlighting some of the characteristics discovered during this effort:

- Research experiences engage students to continuously examine and reevaluate goals, objectives, procedures, data collection and analysis, solution paths, and so on. This dynamically changing learning environment challenges students, but also enables them to learn important problem solving skills in a learning environment that is multidisciplinary and interdisciplinary.
- Research problems are ill-structured and complex because they require students to use many cognitive operations, integrate multiple areas of domain knowledge, and work in a team environment where technical skills from many disciplines need to be integrated, and where interpersonal skills are essential and required for successful completion of the project.
- During all project stages, the research problem solving process is not predictable or convergent, but rather requires the integration of several cognitive, content, and disciplinary domains.
- Although research problems can be complex and ill-structured, there is moderate structuredness when considering the nature of the research team and the research environment, which is typically comprised of several layers of mentors (faculty, postdoctoral associates, graduate students, and other supporting personnel) who provide guidance and structure throughout the research process.
- Research problems lend themselves to a certain degree of independence in problem solving, which in itself is a challenge for students and serves to promote a sense of initiative and ownership of the problem solving process. This challenge is partially offset by the multifaceted team nature of the research problem.

These characteristics of UR problems highlight that research problems are well-suited for PBL implementation in the classroom. This is particularly important when considering that only a small percentage of our STEM undergraduates ever get exposed to UR settings and most of these students are the top students, who are also more likely to go to graduate school and be retained in STEM fields.

Recommendations for Implementation of Research Problems into the Classroom via PBL

Given what has been learned during this effort, the following is a list of some recommendations for integrating research problems into the classroom:

- At the core, research problems have to lead to discovery, whether that discovery is new knowledge, a new technology, a new process or method, and so on. The findings herein suggest that students were challenged by the process of research and certainly the management and planning that goes into research problems. Traditionally, in coursework, students work on problems that have a concrete and clear finale, but the nature of research is such that discovery can be an ongoing process and one that promotes lifelong learning. This way of thinking about problem solving challenges students, but is also something that is important for their problem solving development. It is thus suggested that students at all academic disciplines and levels be introduced and educated on the nature of research.
- Considering that research problems require the integration of multiple disciplinary domains, in knowledge, skills, and attitudes, a suitable place for such experiences in the curriculum may need to be upper-level courses where students are more likely to have the cognitive ability to balance all these domains. Yet with the right planning and mentoring, underclassmen could also be exposed to the nature of research in a way that is well-structured and suitably complex (i.e., not too simple, but not too complex).
- As evidenced from the findings of this paper, undergraduate research problems require students to spend significant time collecting data, selecting methods, setting up procedures for data collection, analyzing data, as well as managing the project. This suggests that for hands-on work, an ideal place for research problems in the curriculum may be laboratory courses or capstone projects. Traditionally, in laboratory courses, experimental setups and detailed procedures are already in place for students to simply go in and take data, but maybe there can be a way for students to be given all the necessary equipment, instrumentation, and materials (as well as a problem statement and goals), but have the opportunity to develop the experimental setup and procedures on their own, collect data, and analyze the data to meet the deliverables outlined in the problem statement. All

this is not to say that research problems don't fit in the traditional lecture-based classroom. Rather, they need to be creatively incorporated to fit the existing class structure. For example, presentations by researchers describing the process of scientific inquiry might substitute a few lectures, or a contemporary research study can serve as a basis for in-class discussion.

- Similar to PBL having different models of implementation, research problems can certainly be integrated into a traditional lecture-based course and this integration could be achieved in many ways (whether it be that a published research study becomes a topic of discussion to illustrate not only relevant concepts but also the process of research as discovery or a presentation by a leading researcher or graduate student on their research problem, methods, and analysis).
- Although a key attribute of undergraduate research problems is the independent nature of task completion, given the length of time required to complete a research problem, it may be best for students to work in teams during classroom-based research problems in order to meet the time constraints of a typical classroom. The independence could still be implemented by allowing students to take ownership of a specific facet of the research problem.
- Given the multidisciplinary and interdisciplinary nature of research problems, it would be ideal for a curricular structure to allow students to work with individuals (students, faculty, and other supporting personnel) from other disciplines. If the curricular structure doesn't allow for this, faculty should encourage their students to seek collaborators or consultants (whether these are students, faculty, or professionals) from disciplines outside of their own. This would at least allow students to be exposed to domain knowledge, skills, and attitudes from other disciplines and perspectives.

Future Research Directions

Limited studies have looked into understanding how different problem solving experiences enable different cognitive abilities and learning outcomes for the problem solver. This study focused on one type of problem solving experience, but there are certainly other types of problems and experiences. Future research directions could thus entail the implementation of similar methods to understanding other types of learning experiences. For example, authentic learning experiences such as industry experiences, service learning projects, and design projects could be examined through the same theoretical lens. Ultimately, by understanding how different problem characteristics influence students' learning outcomes, researchers can provide valuable insight to educators on how to teach different types of problem solving in the classroom. PBL offers a strong foundation to provide innovative models that can support different types of problem solving experiences in the classroom.

Limitations

Very few empirical studies have examined how different problem solving experiences enable different cognitive abilities of the problem solver. The current study used the theoretical framework of Jonassen and Hung (2008) to examine the structure of the problems encountered by engineering and science students during UR experiences. Although the current study has valuable implications both for PBL literature and STEM education, there are several limitations that need to be noted. First, the research design used herein cannot be strictly referred to as a traditional pre-and-post, but is rather a modified version of a pre-and-post design. Due to the participant confidentiality concerns, we were unable to ask for identifying information and thus were unable to link individual responses from the pre-survey to the post-survey. In order to gauge the differences occurring from the pre-survey to the post-survey, we compared aggregate information collected at these two time points. Although this design still yielded interpretable aggregate data, traditional linked pre-and-post design is likely to lead to more confirmatory conclusions.

Furthermore, another feature of the research design presented a limitation. Namely, sample size differed depending on the variable analyzed. This resulted from some participants choosing not to respond to some of the survey questions, resulting in missing data. Although one approach to dealing with this issue is to eliminate all responses from participants with any missing information, we decided to keep complete responses from participants that had incomplete fields due to the relatively low overall sample size and valuable information contained in the complete fields. In the future, this limitation can be counterbalanced by collecting more information, enticing participants to provide complete responses to all of the items, or excluding all missing data from the analyses.

The next limitation pertains to the scaling of survey items pertinent to how well-defined the project stages were. First, the survey used for this purpose is newly developed and might be failing to detect true differences between the project stages. If this is the case, then our conclusion that students report the project stages to be similarly defined is not substantiated. Second, providing students with the seven stages might have prompted them to think of the project in a more defined way, and therefore affect their responses to questions regarding the degree of definition present in the project. Both of these limitations can be resolved by collecting more validity evidence for the survey and conducting focus groups to gain a better understanding of student perceptions.

Lastly, the final limitation of the current research effort is the sole reliance on student self-reporting. There are numerous issues related to using self-reported data, including participants' possible inability to provide an accurate self-assessment and socially desirable response patterns. To offset these limitations inherent to self-reported data, other relevant data sources, such as faculty surveys and direct observations, could be triangulated with the present dataset. Such triangulation could potentially strengthen the inferences made

based on this research. Another limitation inherent in all Likert type scales is the untested assumption of linear scalability. Although the students responded to each survey item on a 10-point scale, we cannot claim that a response of 8, for example, indicated a doubled agreement from the response of 4. However, it is reasonable to assume that a response of 8 indicated a stronger agreement when compared to a response of 4. Due to the untested, but presumed, assumption of linear scalability, means and standard deviations reported here are estimates of the endorsement strength and should not be used for strict relative comparisons.

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